# *Elliptic flow of thermal photons from hydrodynamics*


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# *Motivation*

- Characteristics of an expanding thermal system
  - Radial flow
  - Elliptic flow ($v_2$)

- Elliptic flow in heavy ion collisions
  - Hadrons:
    - Abundant, but freeze out from strong interactions late in the fireball evolution.
  - Photons:
    - Freeze out immediately, but rare
    - A window on early evolution stages

- We predict photon emission and elliptic flow
  - Here: Ideal hydrodynamics.

# Hydrodynamics

P. Kolb et al, PRC 62: 054909, 2000.

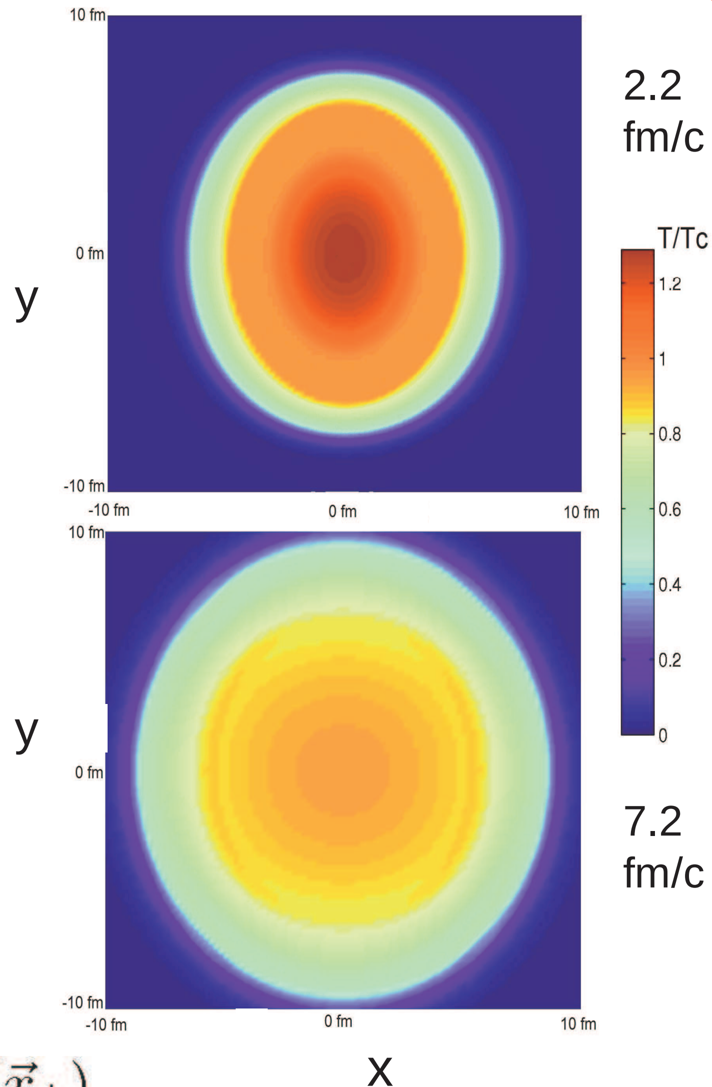
$$\dot{n}_B = -n_B\,(\partial\cdot u)$$
$$\dot{\varepsilon} = -(\varepsilon+p)\,(\partial\cdot u)$$
$$\dot{u}^\mu = \frac{\nabla^\mu p}{\varepsilon+p}$$

- Ideal fluid dynamics

- Flow driven by pressure gradients: $\boxed{\nabla^\mu p}$

Temperature

***b=7 fm, Au+Au***




- Photon rate $\sim \int [\ldots]\, e^{-\frac{k\cdot u(x)}{T(x)}}\, d^4x$

$$\frac{k^\mu u_\mu(x)}{T(x)} = \frac{\gamma_\perp(x)}{T(x)}(E_\gamma \cosh\eta - \vec{k}_\perp\cdot\vec{v}_\perp(x))$$
$$= \frac{\gamma_\perp(x)}{T(x)}E_\gamma(\cosh\eta - \ v_\perp(x)\ \cos\theta_{uk})$$

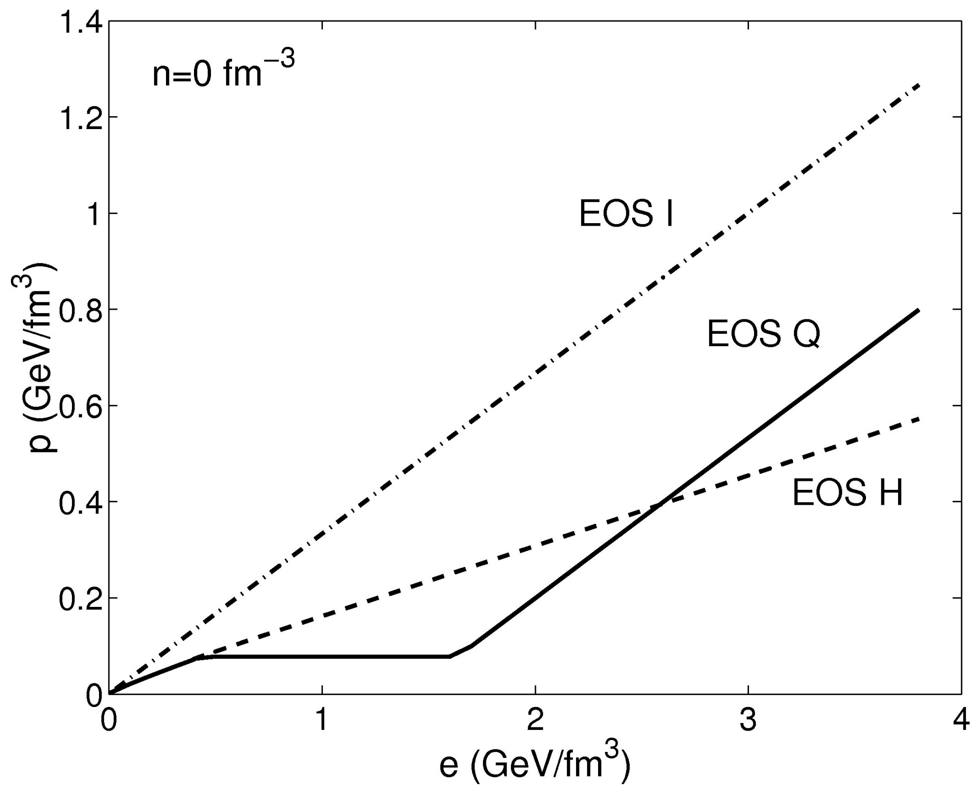
- $v_2$ affected by anisotropies of $\vec{v}_\perp(\vec{x}_\perp)$ and $T(\vec{x}_\perp)$

# Hydrodynamic parameters and EOS

- Maxwell constructed EOS
  - Chemically equilibrated hadron gas to thermal freeze-out.

-Initial time, $\tau_0$=0.2 fm/c
  - Changed from 0.6 fm/c
  - To capture/simulate pre-equilibrium photons

- Initial $s_0$=351 GeV/fm$^3$




Equation of state from Kolb, Sollfrank and Heinz, PRC 62 054909

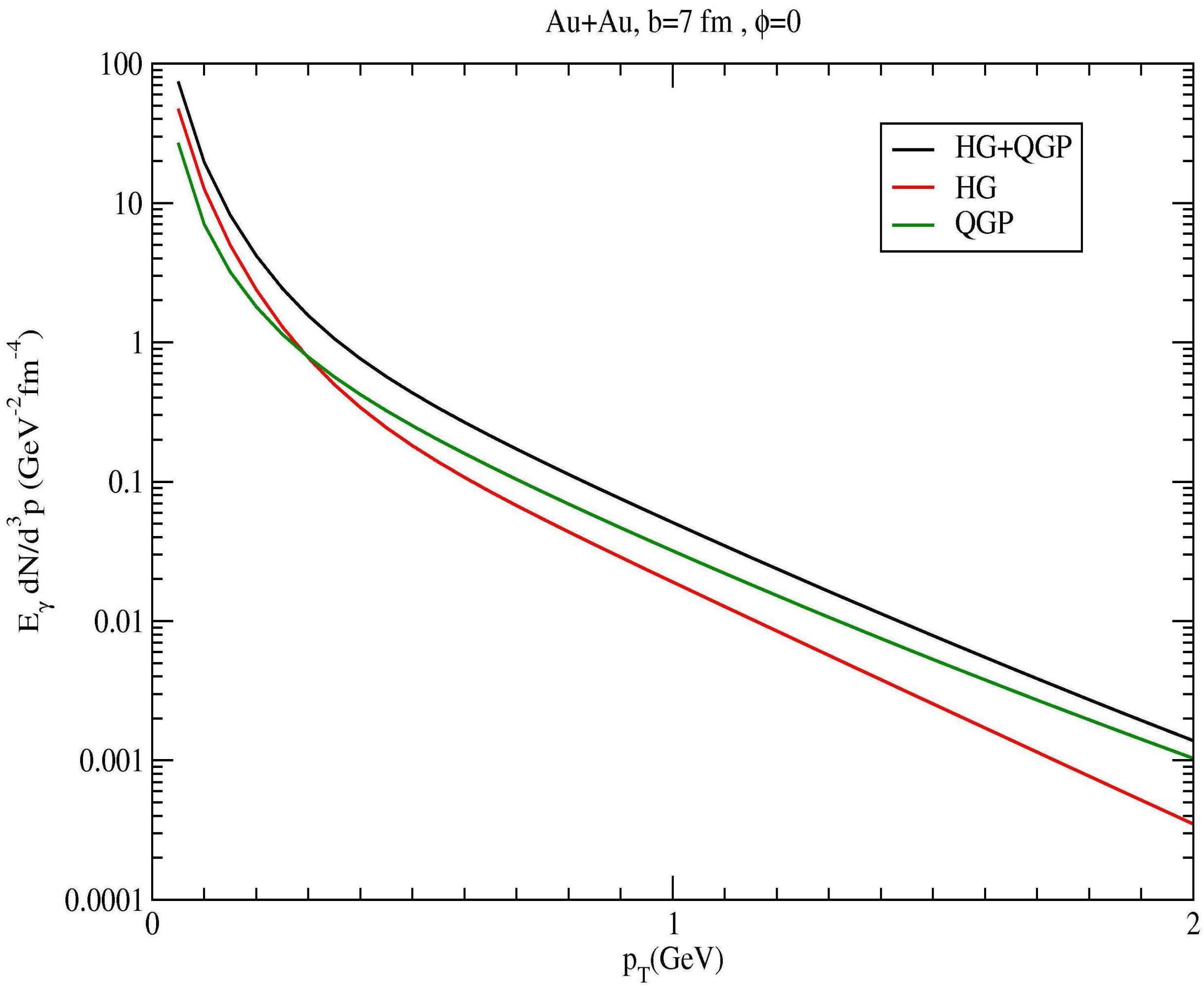
# *Anisotropic flow*

- Characterized by the azimuthal Fourier coefficients of spectrum:

$$\frac{dN(b)}{d\phi\, p_T\, dp_T\, dY} = \frac{dN(b)}{2\pi\, p_T dp_T\, dY}\left[1 + 2v_2(p_T, b)\cos(2\phi) + \ldots\right]$$

$$\Rightarrow \quad v_2(p_T, b) = \frac{\int d\phi\, \cos(2\phi)\, E_\gamma \frac{dN(b)}{d^3p}}{\int d\phi\, E_\gamma \frac{dN(b)}{d^3p}}$$

# *Single Photon Spectra*




- Use photon emission in local rest frame boosted to lab frame by:

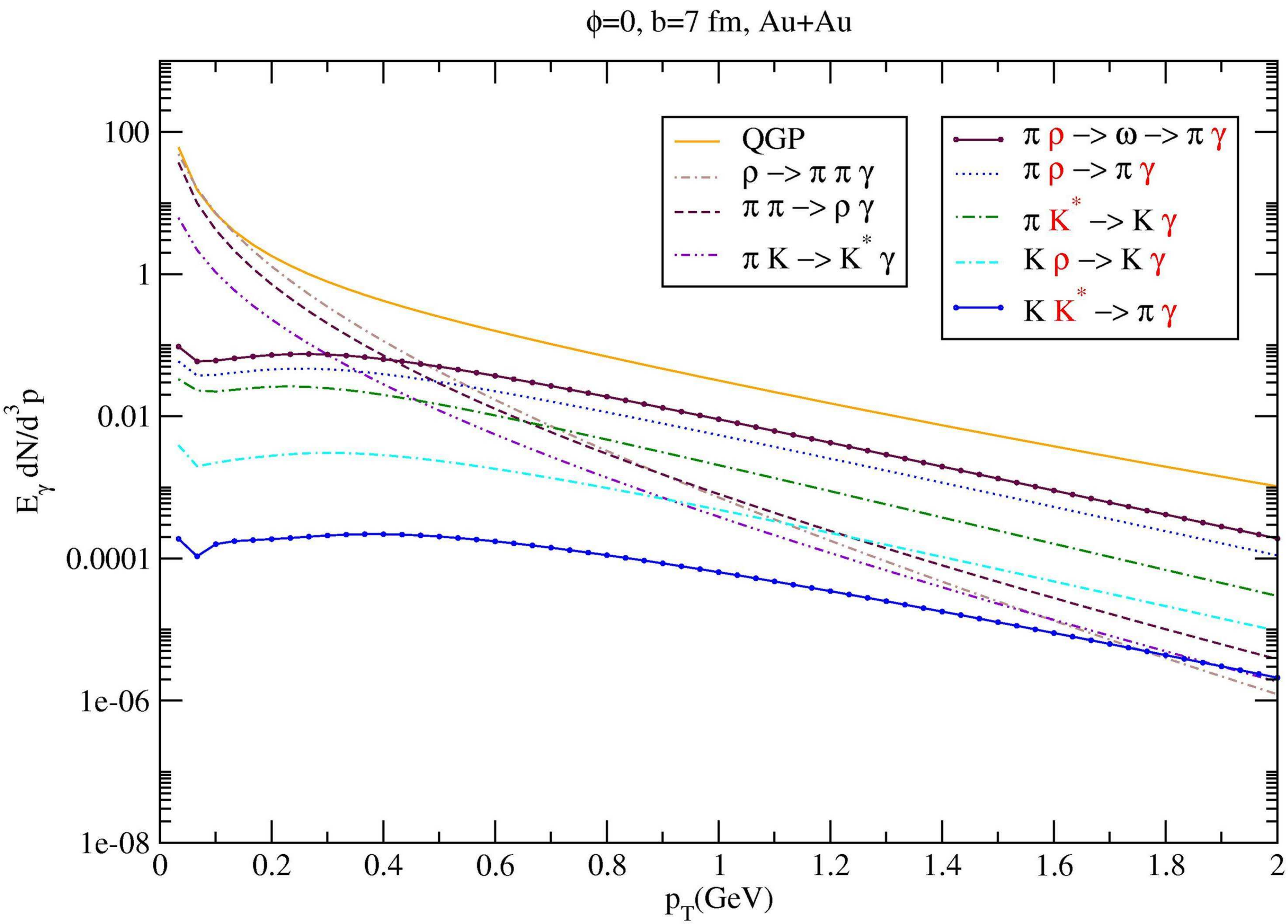
$$\boxed{\frac{k}{T} \longrightarrow \frac{k^\mu u_\mu(x)}{T(x)}}$$

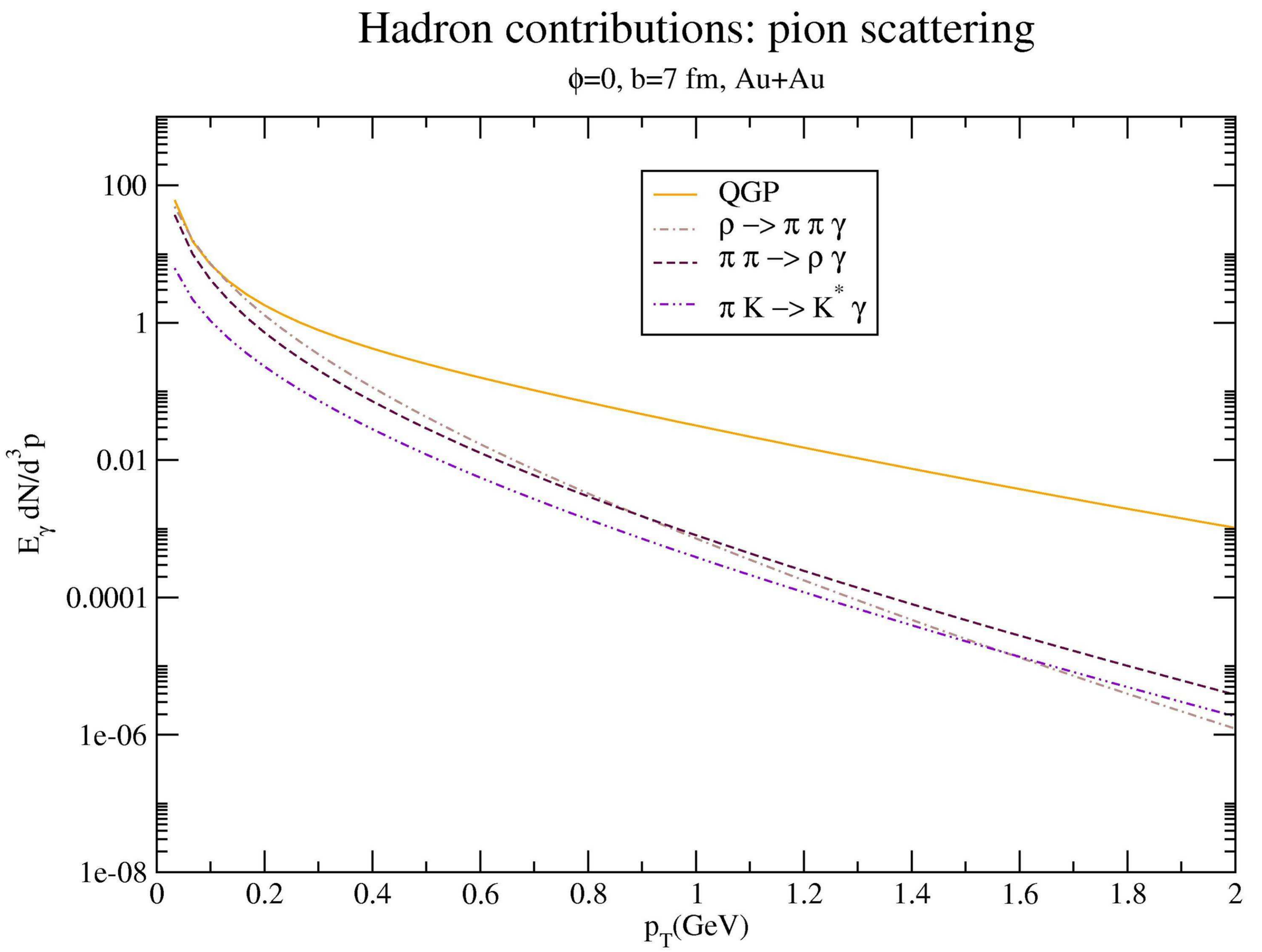
- $u^\mu(\vec{x}_\perp), T(\vec{x}_\perp)$ from hydrodynamics

- QGP rate from Arnold, Moore and Yaffe, JHEP 0112, 2001.

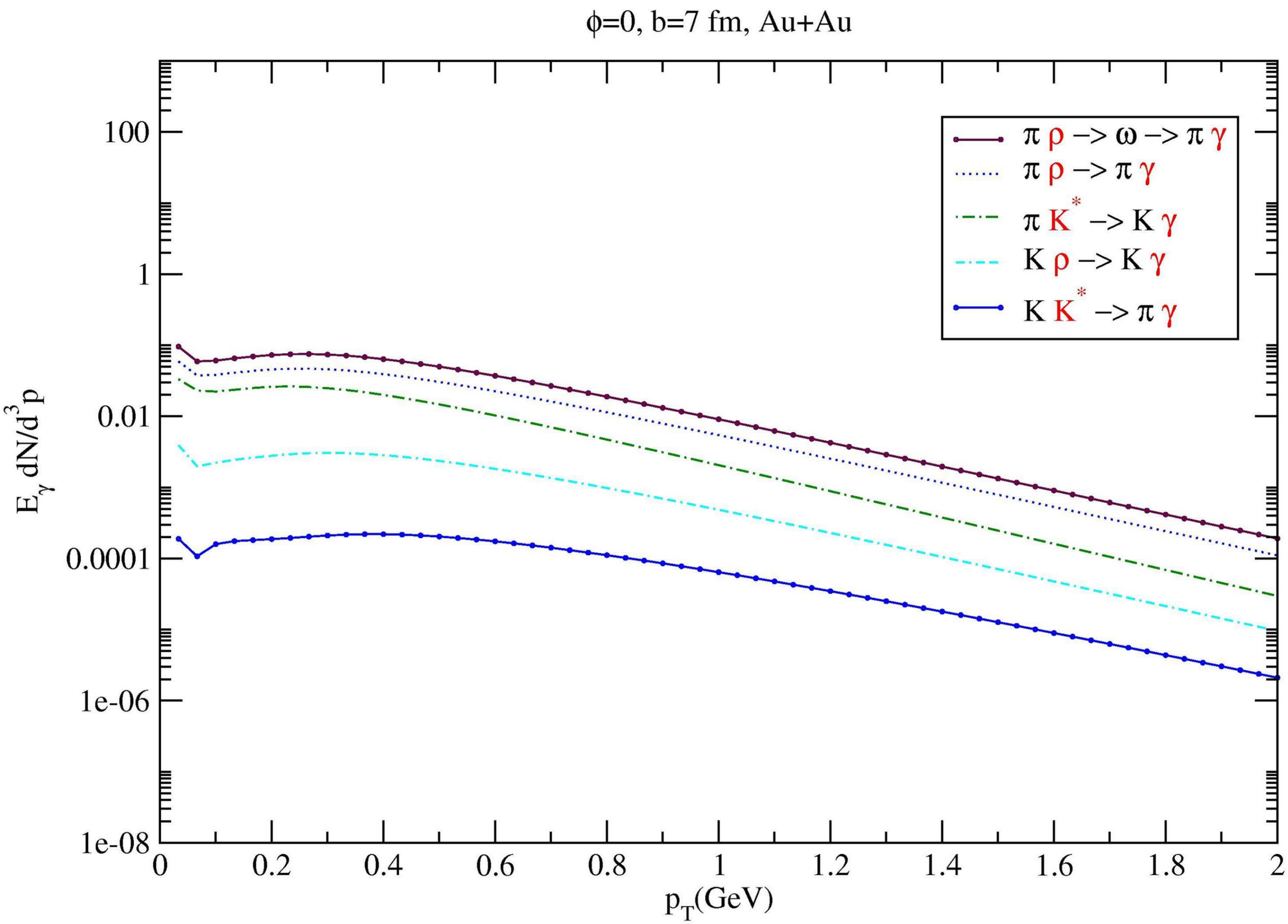
- HG rate from Turbide, Rapp and Gale, PRC 69, 2004.

# Relative contributions from hadron gas phase

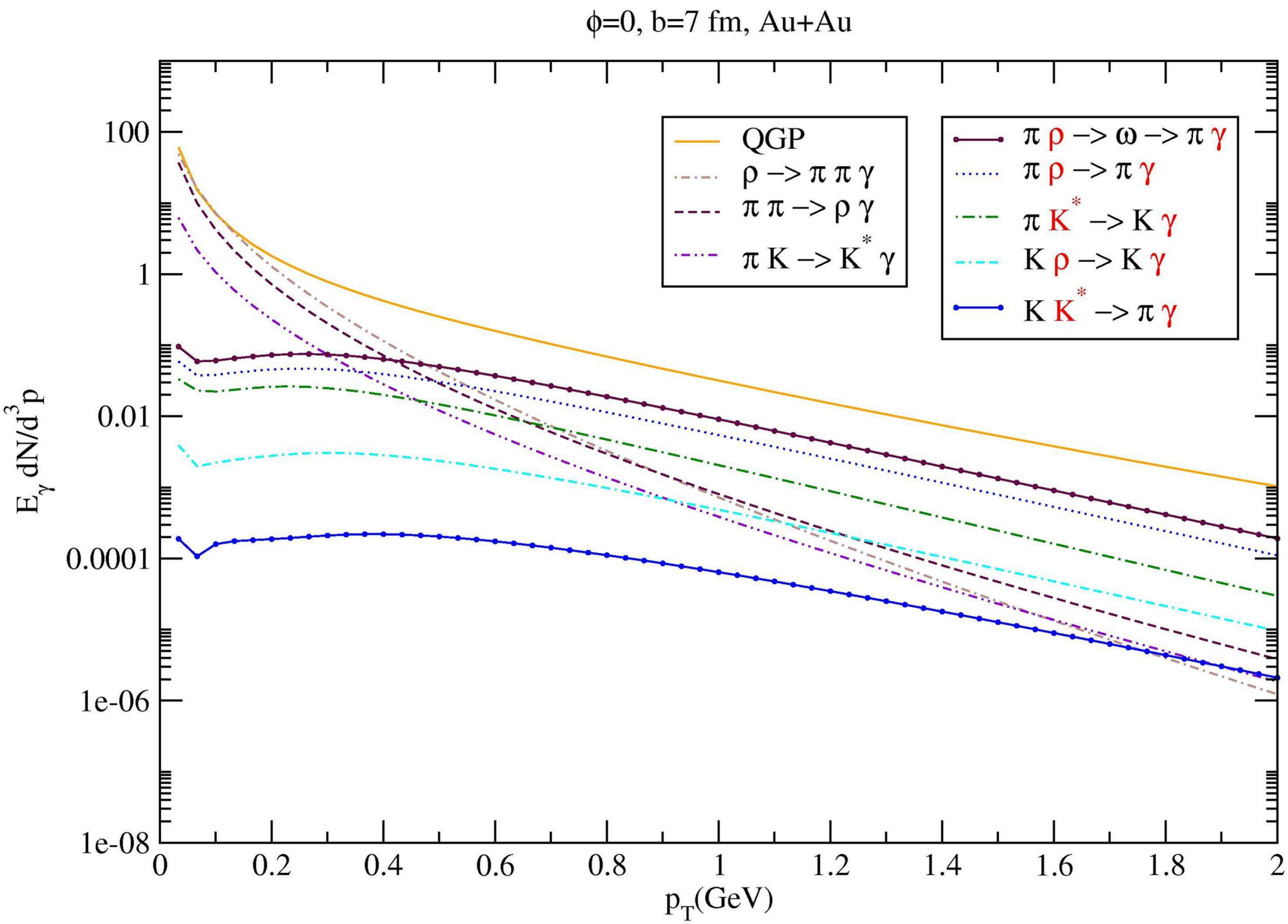



Hadron contributions: pion scattering
φ=0, b=7 fm, Au+Au
QGP
ρ -> π π γ
π π -> ρ γ
π K -> K* γ
100
1
0.01
0.0001
1e-06
1e-08
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
p_T(GeV)
E_γ dN/d^3p

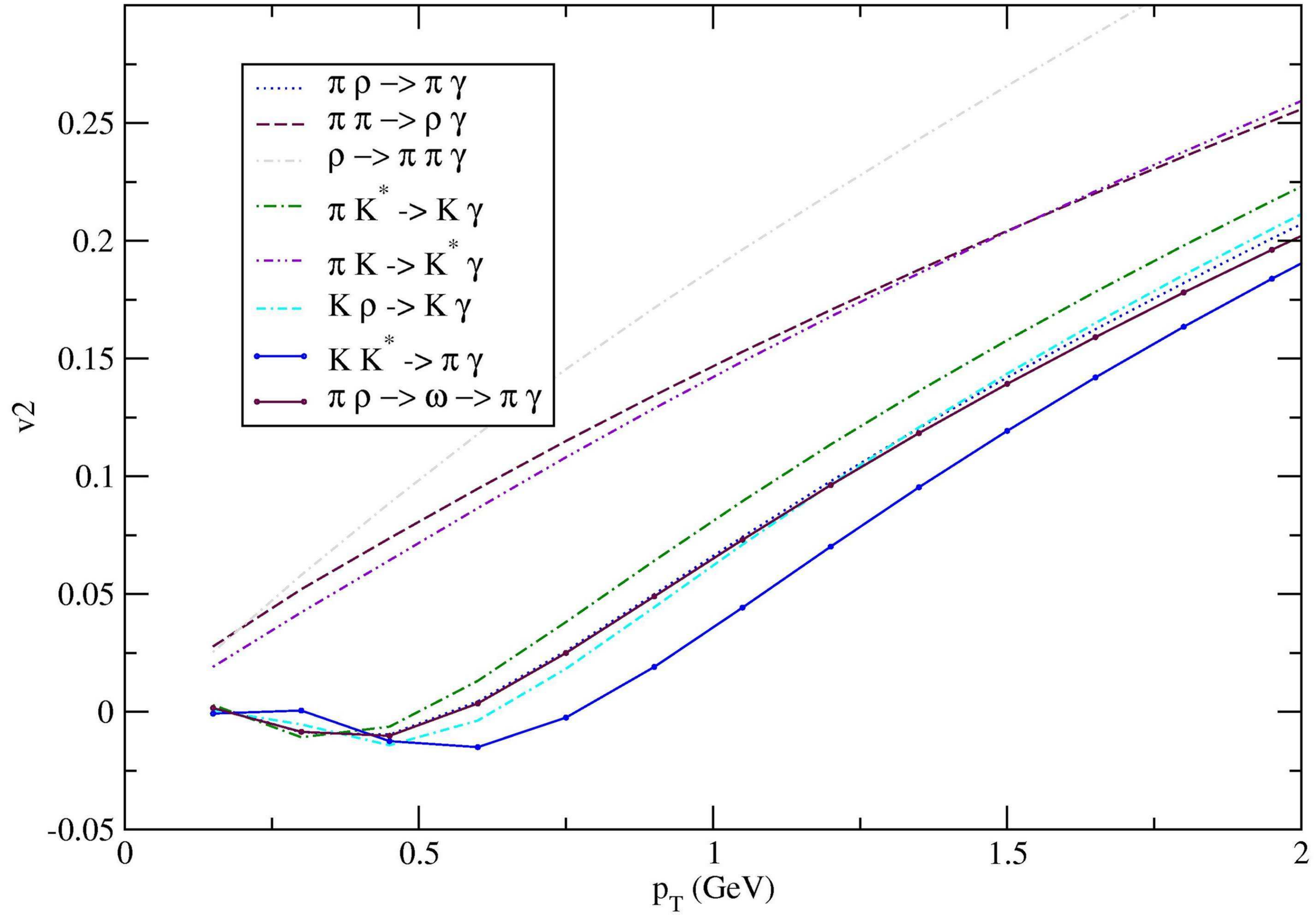
# Hadronic contributions: vector mesons –> photon conversion



# Relative contributions from hadron gas phase



# Eliiptic flow contributions from hadron gas phase



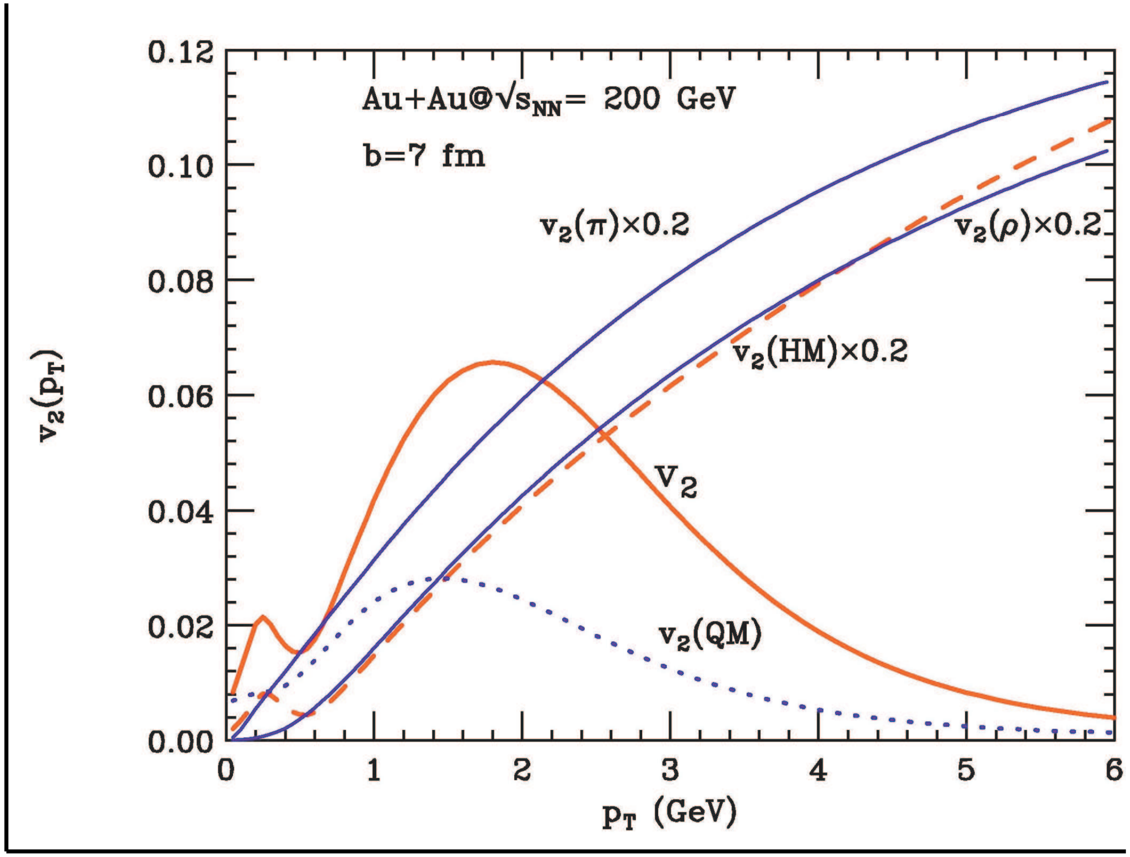
# Photon $v_2$

- Hadronic photons track…
  - $\pi$'s for $p_\perp < 400$ MeV
  - $\rho$ mesons for $p_\perp > 400$ MeV
  - Structure in $v_2$ around $p_\perp \sim 400$ MeV

- QGP photons track quark flow
  - small at high $p_\perp$ (early times)

- Total photon $v_2$ dominated by QGP for $p_\perp > 1\sim2$ GeV.
  - $v_2$ decreases at high $p_\perp$

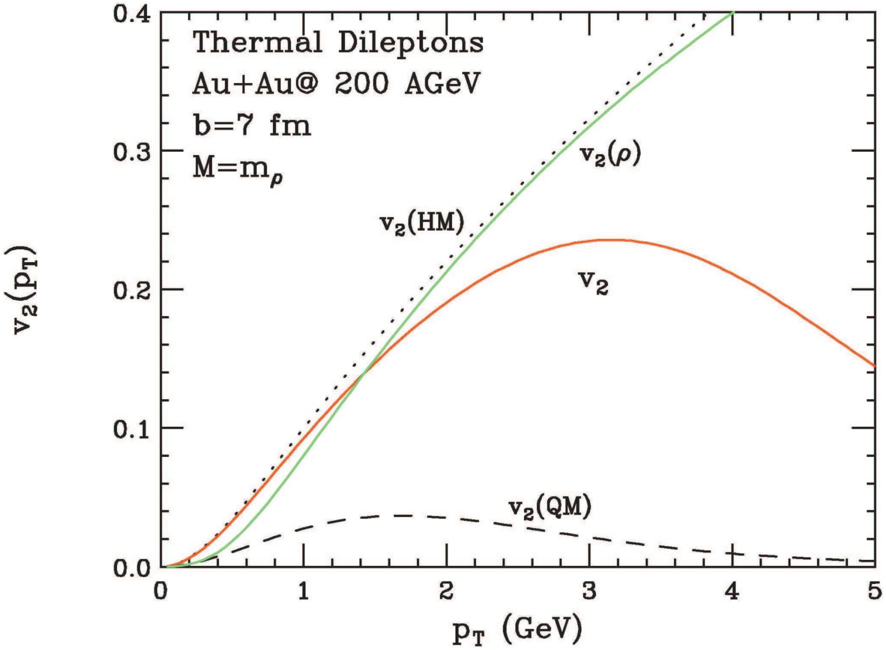
- Hydrodynamic prediction = upper limit
  - viscosity will further reduce $v_2$ at large $p_\perp$
  - Structure around 400 MeV should be reliable




As taken from Chatterjee, Frodermann, Heinz, and Srivastava. PRL 96: 202302

# *Virtual Photons: Dileptons*

$M = m_\rho$

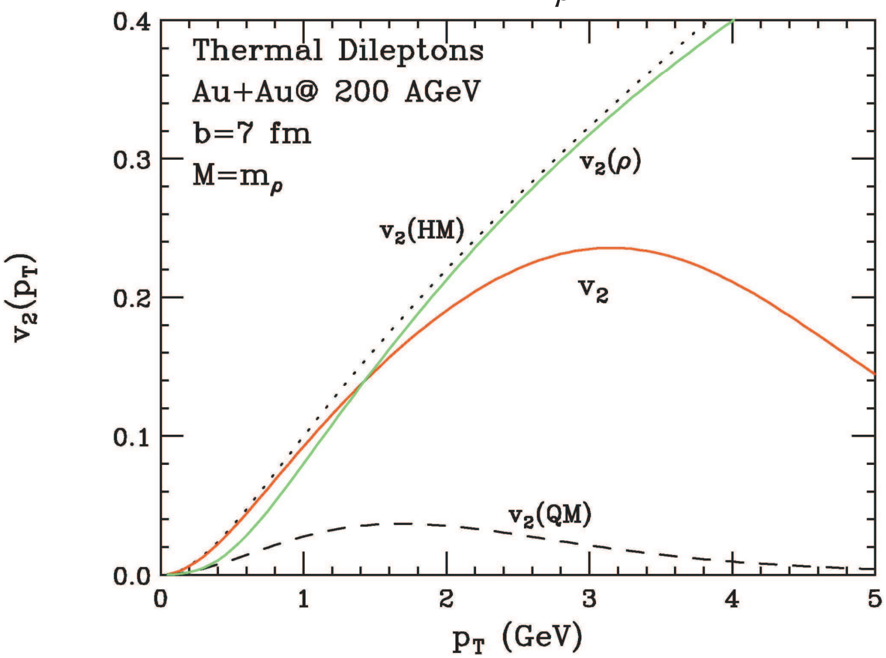


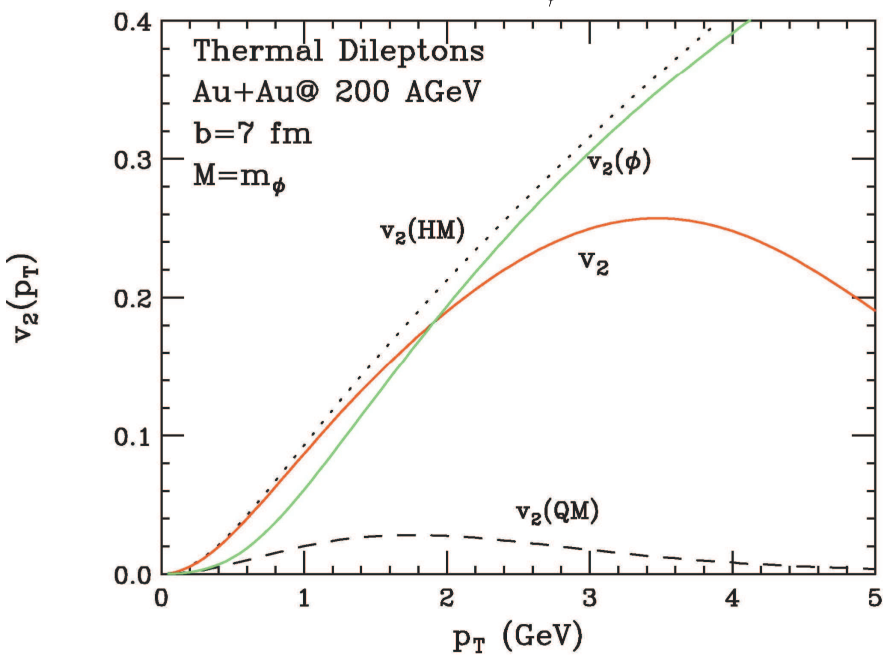

Gale, Srivastava, Chatterjee, and Heinz, (to be published)

- Dilepton $v_2$ qualitatively similar to photon $v_2$

# *Virtual Photons: Dileptons*

$M = m_\rho$ $M = m_\phi$



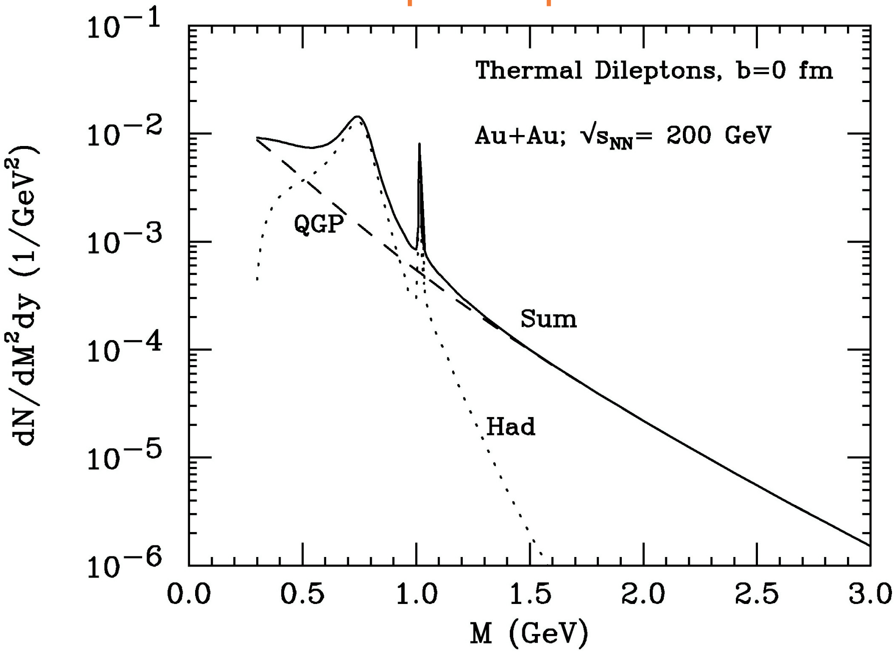




Gale, Srivastava, Chatterjee, and Heinz, (to be published)

- Dilepton $v_2$ qualitatively similar to photon $v_2$
- Near $\rho$, $\phi$ resonances, dilepton $v_2$ tracks $v_2(\rho, \phi)$ up to $p_T$~1.5 GeV

# *Mass dependence of $p_\perp$*- integrated dileptons

Dilepton Spectrum

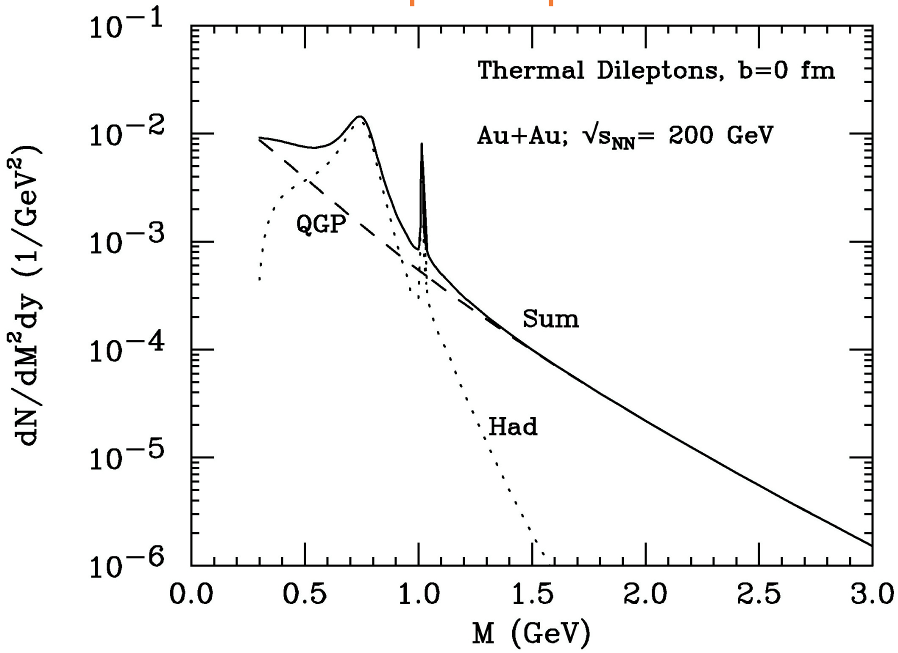



Gale, Srivastava, Chatterjee, and Heinz, (to be published)

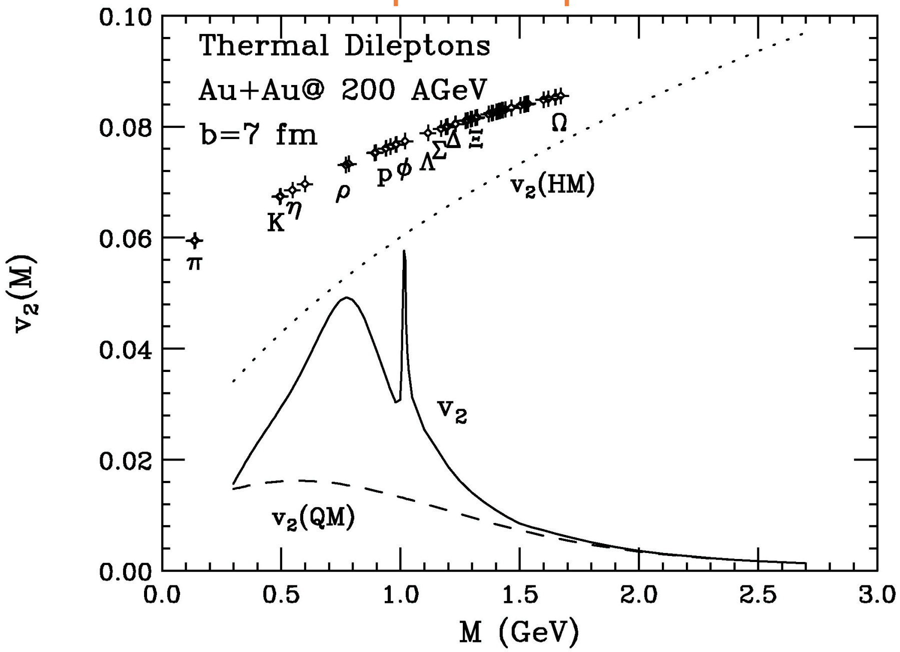
- Strong variation of relative QGP/HG contributions as function of dilepton mass *M*

# *Mass dependence of $p_\perp$*- integrated dileptons

## Dilepton Spectrum




## Dilepton Elliptic Flow



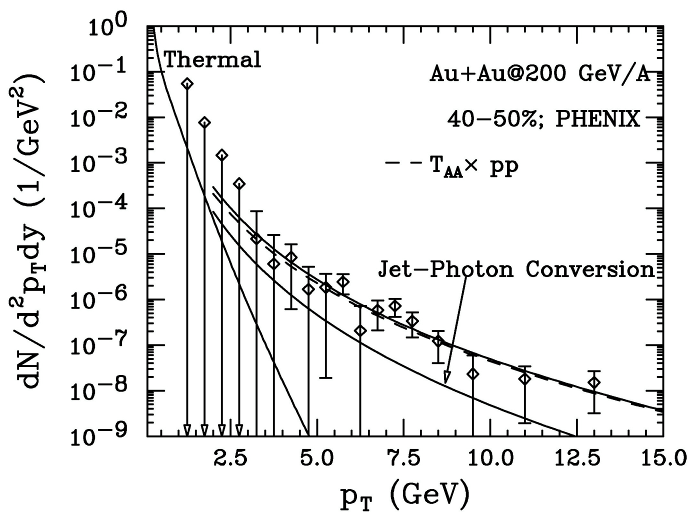

Gale, Srivastava, Chatterjee, and Heinz, (to be published)

- Strong variation of relative QGP/HG contributions as function of dilepton mass *M*
- Near $\rho$, $\phi$ resonances, dilepton $v_2$ approaches hadronic $v_2$
- For dilepton mass > 1.5 GeV, QGP contribution dominates

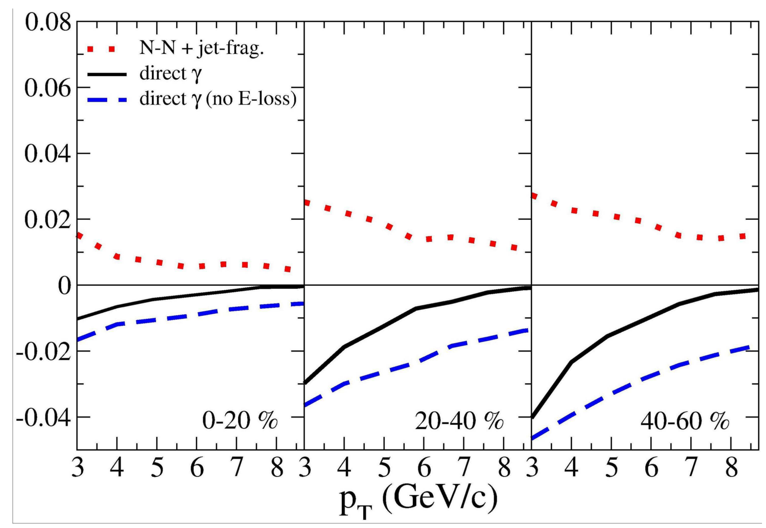
# Future steps:

- Resonance background
  - Compute photons form post freeze-out hadron decays ($\pi^0$, $\eta$, $\eta$', …)
- Include chemical decoupling of hadron abundances at $T_C$=170 MeV into the hadronic EOS
- Pre-equilibrium photons
- Jet contributions at high $p_T$
  - Negative $v_2$ component predicted at high $p_T$. (Turbide, Gale and Fries)

Photon yield with jet-photon conversion. Fries, Müller, and Srivastava PRC 72:041902 (2005)




Photon v2 for direct photons with jet photon conversion. Turbide, Gale, and Fries. PRL 96:032303 (2006)

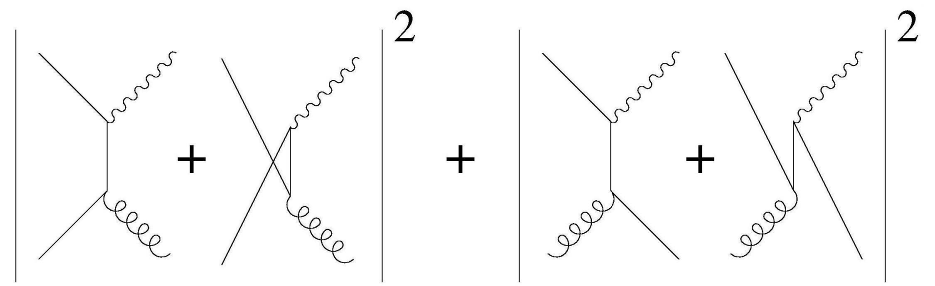


# *Conclusions*

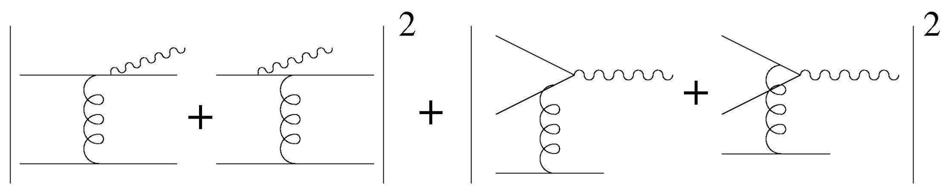
- Photon (real and virtual) elliptic flow tends to zero at high $p_\perp$.
  - Reflects QGP emission and small flow anisotropies at early times.

- Photon $v_2$ from HG tracks hadronic $v_2$.
  - Use as tool to subtract from the total photon $v_2$ the contribution from the hadron gas phase (?)

# Quark Gluon Plasma



2 → 2 Processes



Brem. and Annih. Processes

As taken from Arnold, Moore and Yaffe, 2001

- **Fully equilibrated quark gluon plasma** in a region when QCD becomes perturbative.
  - Assume high T, $g_s << 1$
- 2 → 2, bremsstrahlung, and annihilation processes included.
- Parameterizations taken from Arnold, Moore, and Yaffe, JHEP 0112, 2001.

$$k\frac{d\Gamma_\gamma}{d^3\boldsymbol{k}} = \mathcal{N}T^2\,\alpha_{EM}\,\alpha_s\,n_f\left(\frac{k}{T}\right)\left[\ln\left(\frac{T}{m_\infty}\right) + C_{tot}\left(\frac{k}{T}\right)\right]$$

$$m_\infty^2 = \frac{C_F g_s^2 T^2}{4}$$

$$C_{tot}\left(\frac{k}{T}\right) \equiv \frac{1}{2}\ln\left(\frac{2k}{T}\right) + C_{2\leftrightarrow 2}\left(\frac{k}{T}\right) + C_{brem}\left(\frac{k}{T}\right) + C_{annih}\left(\frac{k}{T}\right)$$

$$n_f(x) = \frac{1}{e^x + 1}$$

# *Hot Hadron Gas*

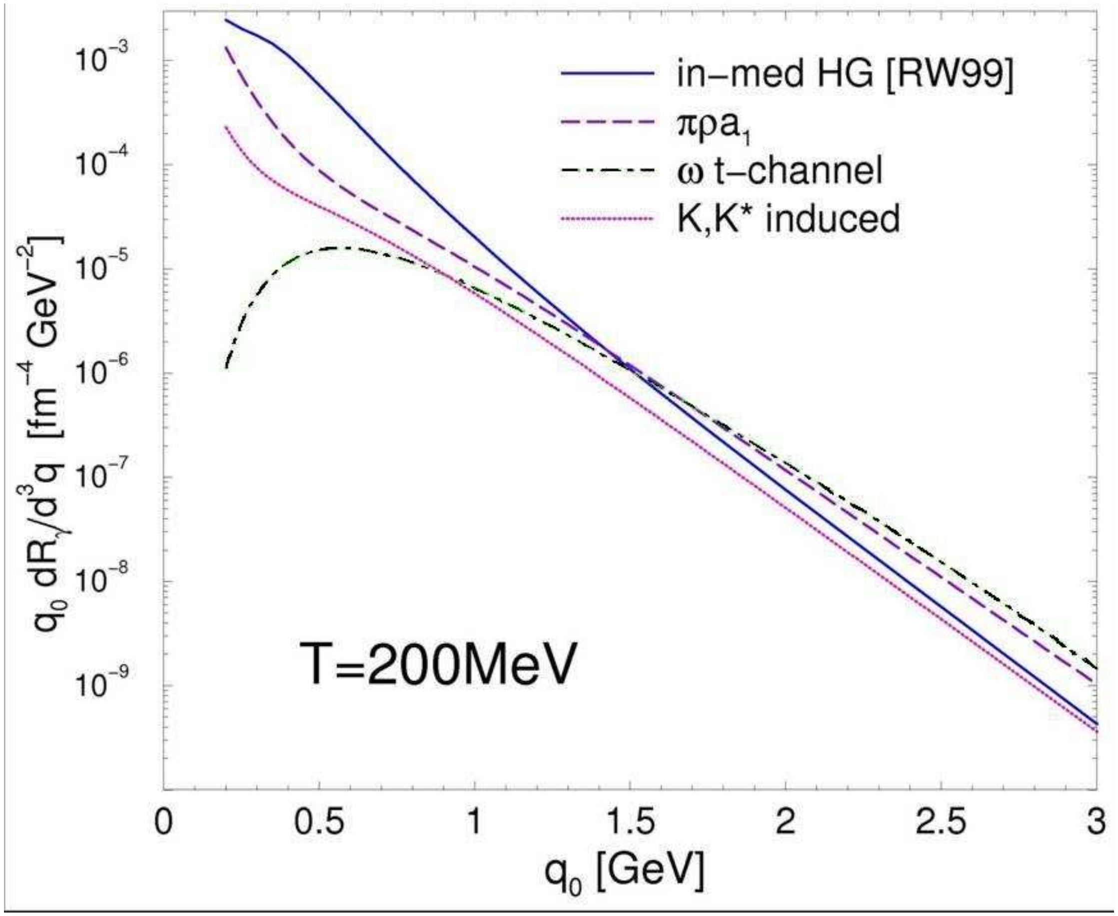
**-Massive Yang-Mills** approach with axial, vector and pseudoscalar fields.

(C. Song, PRC 47, 1993)

- Hadronic form factors.

 -- Dipole Form

- Parameterizations taken from Turbide, Rapp, and Gale, PRC 69, 2004.




Selected Photon Production Rates involving Strange Mesons. (Turbide, Rapp and Gale, 2003)

# *Motivation*

- Abstract Summary here.
- Abstract
  - The elliptic flow, ($v_2$), of particles is one of the significant signatures of a thermally expanding fireball in a relativistic heavy ion collision. Typically, $v_2$ is calculated for abundant particles such as charged pions which decouple from the thermal medium at later times. Photons, however, decouple from the medium upon creation, carrying information for the full fireball duration, particularly information about the early QGP stage. We explore the photon elliptical flow of Au+Au collisions using an ideal hydrodynamical model to describe the collision. There is a strong change in the $p_T$ dependence of the photon elliptical flow as compared to hadronic flow predicted by hydrodynamics. In particular, the high $p_T$ flow reflects the flow generated in the early QGP phase.